ADVANCES IN ELECTROTACTILE STIMULATION FOR PROSTHETIC SENSORY FEEDBACK

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Summary

The electrotactile sensation and pain thresholds are investigated as part of our ongoing efforts to optimize prosthetic sensory feedback.

It was shown that the sensation and pain thresholds elicited by monopolar, 2 mSec wide electrical pulses and delivered via concentric electrodes is a function of frequency.

The characteristic response over 0 - 100 pps frequency range demonstrated a "V" shaped curve for both sensation and pain. A frequency F_m, corresponded to the lowest threshold, and was different from subject to subject. The F_m, however, was constant for both pain and sensation for the same subject. Additional subjects tested for sensation, pain and two point discrimination showed that the F_m for all thresholds was the same.

The average sensation to pain range was constant although several individuals demonstrated about 50% decrease in range from the lowest frequency to the highest.

The sensation and pain thresholds were shown to vary exponentialy as a function of stimulus pulse width. At pulse widths of 10μs the thresholds and their associate range were approximately twice their value that at 1 ms.

Introduction

In a continuing effort to optimize multichannel electrotactile displays for purposes of prosthetic tactile and kinesthetic sensory augmentation, the sensation and pain thresholds have been investigated.

Our previous reports defined the Two Point Discrimination Threshold (TPDT) as a function of body site, laterality, stimulation codes, pulse wide, phase shift frequency and learning, (1,2,3,4). In the course of the studies it was evident that the TPDT could be further decreased by short daily training over fourteen days (4). In that study the smallest TPDT obtained was 6.55 mm which was also the outside diameter of our test electrode. It was therefore considered to further reduce the electrode size for optimal response. Theoretically, such reduction will increase the sensitivity of the stimulus current density due to variations in the skin resistance resulting from routine physiological changes such as skin dryness and perspiration. It was, therefore, considered to investigate first the sensation and pain thresholds for our electrode as a function of stimulus frequency, and thereby estimate the available range for stimulation in the comfortable range.

Experimental Procedures

The experimental apparatus consisted of a Grass stimulator model S4, a high voltage output amplifier designed and constructed in our laboratory, and a stainless steel concentric electrode.

The concentric electrode of 6.55 mm O.D. with a 3.275 mm cathode were made of stainless steel with a ring of PVC insulating the anode from cathode. The cathode area was 8.424 mm^2 and the anode area was 11.84 mm^2.

Stimulus current was monitored by a 10 Ohm resistor inserted in series with the electrode and connected across the input of a 535A Textronix oscilloscope.

Subjects

Fourteen subjects were tested, all male. The subjects were drawn from a junior physiology class, and ranged in age from 18 to 25 with average age of 21.

Protocol

Tests of sensation and pain thresholds were made over the thenar eminence of the dominant palm of each subject. The palms were washed and partially dried, providing moist skin to facilitate stimulus current conduction, and to give consistency to the measurements.

The palm was then placed over the electrode which was partially protruding from a wooden box. No additional pressure was applied other than the weight of the hand.

The stimulus frequency was set at 5 pps at 2 mSec pulse width and the current slowly increased from zero to the point where the subject first detected sensation. The current value was recorded and then further increased to the point where the subject reported pain. The current value for pain was then recorded. The subjects were instructed to indicate pain when the stimulus sensation perceived corresponded to light sting. No further increase into the bearable pain region was allowed.

At the end of each such test, the frequency was reset and the test repeated in the same manner for 15, 30, 50, 70 and 100 pps. Test were also made for pulse widths of 10, 100, 1000and 10,000 μ Sec. to determine the optimal width. Once the Fm for a subject was determined, four tests were made at Fm and f =100 for the sensation-pain thresholds at each of the above pulse widths.

All subjects underwent a five minute instruction period regarding the experiment and the required information. In addition, another ten minutes of testing was administered to each subject to acquaint him with the pain and sensation thresholds as well as the actual experimental procedures. Data recordings were initiated after the subject performed satisfactorily in the preliminary test. Three trials were recorded for each subject for purposes of repeatability studies.

Results

Data

A typical data plot of three tests of sensation and pain thresholds for one subject is shown in figure 1. The lower set of three curves shows sensation threshold and the upper set of three curves shows the pain threshold. Both sensation and pain threshold demonstrated a characteristic "V" shaped curve over the frequency range considered (Figs. 2 & 3). For brevity, the following definitions were made:

MST - Minimum Sensation Threshold; the absolute lowest value of the sensation curve over the frequency range of 0 - 100 pps.

MPT - Minimum Pain Threshold; the absolute lowest value of the pain curve over the frequency range of 0 - 100 pps.

F_m - Minimum Frequency; the frequency at MST or MPT.

SPR - Sensation to Pain Range; the current range between sensation threshold to pain threshold.

FBW - Functional Band Width; the frequency range corresponding

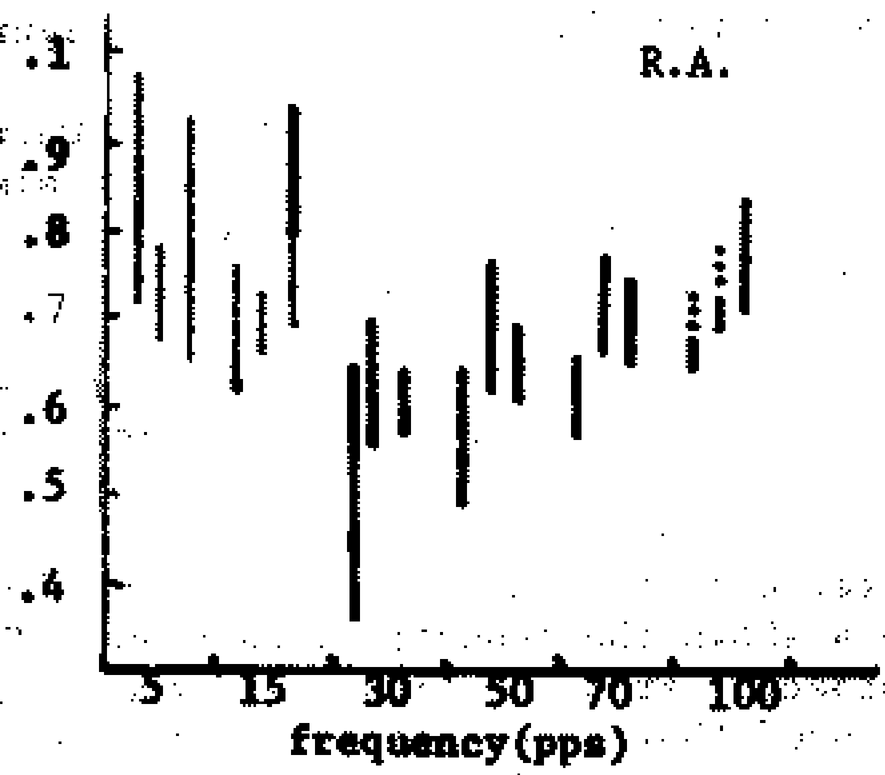

Figure 1. Sensation and pain threshold data for a typical subject.

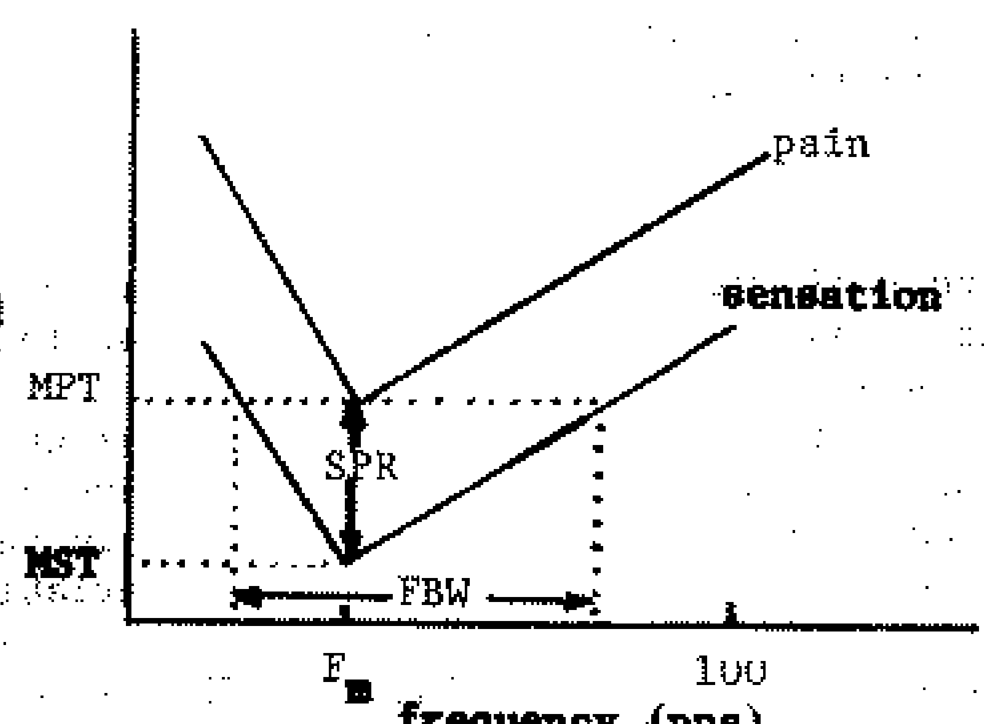

Figure 2. typical S and P threshold curves and the associated definitions.

to the intersection points of the line T(f)=MPT with the sensation curve

Sensations and Pain Thresholds

The average sensation and pain thresholds for the data of figure 1 is shown in figure 3.

It is evident that both sensation and pain thresholds are functions of frequency with a minimum at a specific frequency F_m. The F_m, as is also seen from the figure, is the same for the sensation and pain response.

The data confirms our earlier findings (1) regarding the Two Point Discrimination Threshold, where a characteristic "V" shaped response with a minimum F_m, was common to all subjects. The increased sensitivity of tactile receptors to electrical stimulus of a specific frequency, which is different from subject to subject is apparent.

In order to test the possibility that the sensation-pain F_m is also the TPDT F_m, a TPDT test was administered to two subjects whose sensation-pain data was previously obtained. Figure 4 shows the sensation, pain and TPDT data as a function of frequency for one subject. From the figure and the data from the second subject, it could be concluded that the sensation, pain and TPDT response indicates increased sensitivity at a specific frequency F_m, which is common to all three.

Furthermore, it seems that the F_m is an individual property of each subject and is different from subject to subject as was also shown for the TPDT (1). The possibility of the nervous system being finely tuned to a specific frequency F_m, which allows increased perception is proposed. No concluding evidence could be given here as to the physiological mechanism of such fine tuning as F_m, and as to whether it is a peripheal or central property of the CNS.

Table 1 shows the F_m distribution for the subjects tested. Again, as was seen in our earlier studies (1,3,4), most subjects demonstrate F_m range of 5-50 pps with occasional individuals having F_m at 70 pps. Out of over 90 subjects tested since the initiation of this work none had F_m over 70 pps.

Sensation to Pain Range (SPR)

The sensation to pain range (SPR) was measured for each frequency point of each subject and was plotted as a function of frequency. The mean range for all subjects as well as the highest and lowest ranges are shown in Figure 5.

It is apparent from the figure that the average SPR is not frequency dependent, and therefore, is constant over the frequency range. Several individuals, nevertheless, demonstrated sharp decrease in SPR as shown in the highest curve, in Figure 5, where 50% decrease is apparent. Large SPR variability is observed from subject to subject. As shown in Figure 5, the highest SPR measured was some 20 - 30 times the lowest range obtained. The mean SPR is about 1 mA, indicating that current density variation of 0.12 mA/mm^2 is allowed to compensate for variations in skin impedance within the comfortable perception range. The current density range corresponding to the highest and lowest SPR are 0.3 mA/mm^2 and 0.012 mA/mm^2, respectively.

Functional Band Width (FBW)

Since stimulus frequency is considered as an information transmission code, it is of interest to assess the Functional Band Width (FBW), or the frequency range allowable below the pain threshold and above sensation threshold (see Figure 2).

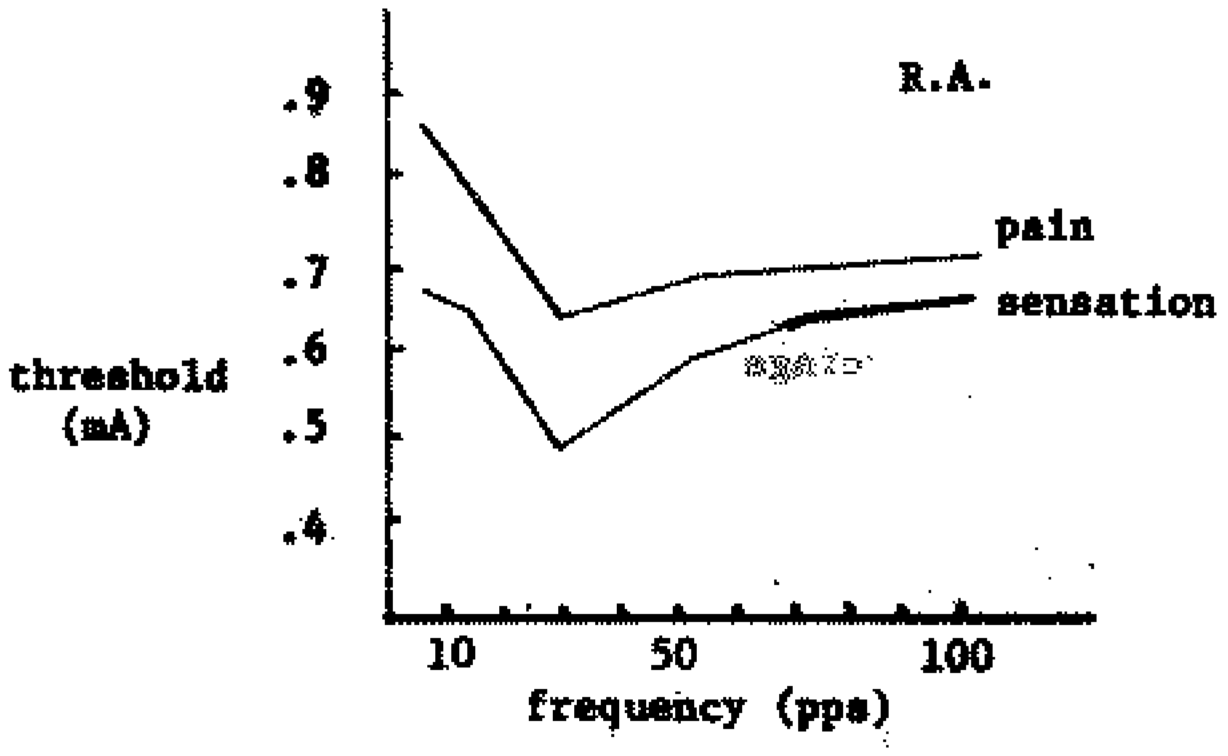

Figure 3. Average S and P thresholds as a function of frequency for the data of figure 1.

TABLE I

F_m	5	15	30	50	70	100
subjects	4	4	4	1	1	0

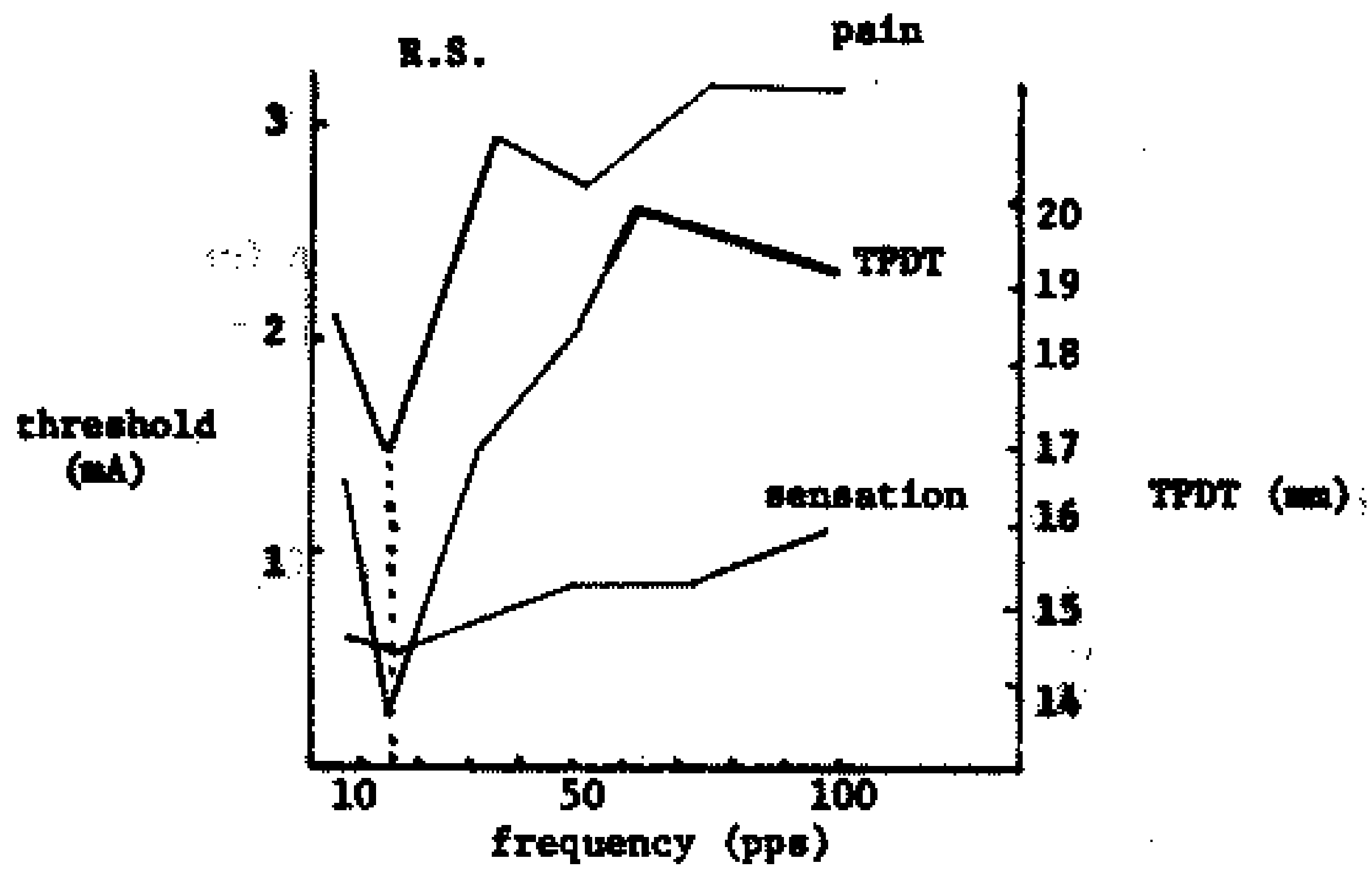

Figure 4. Sensation, pain and TPDT curves for one subject showing the common F_m.

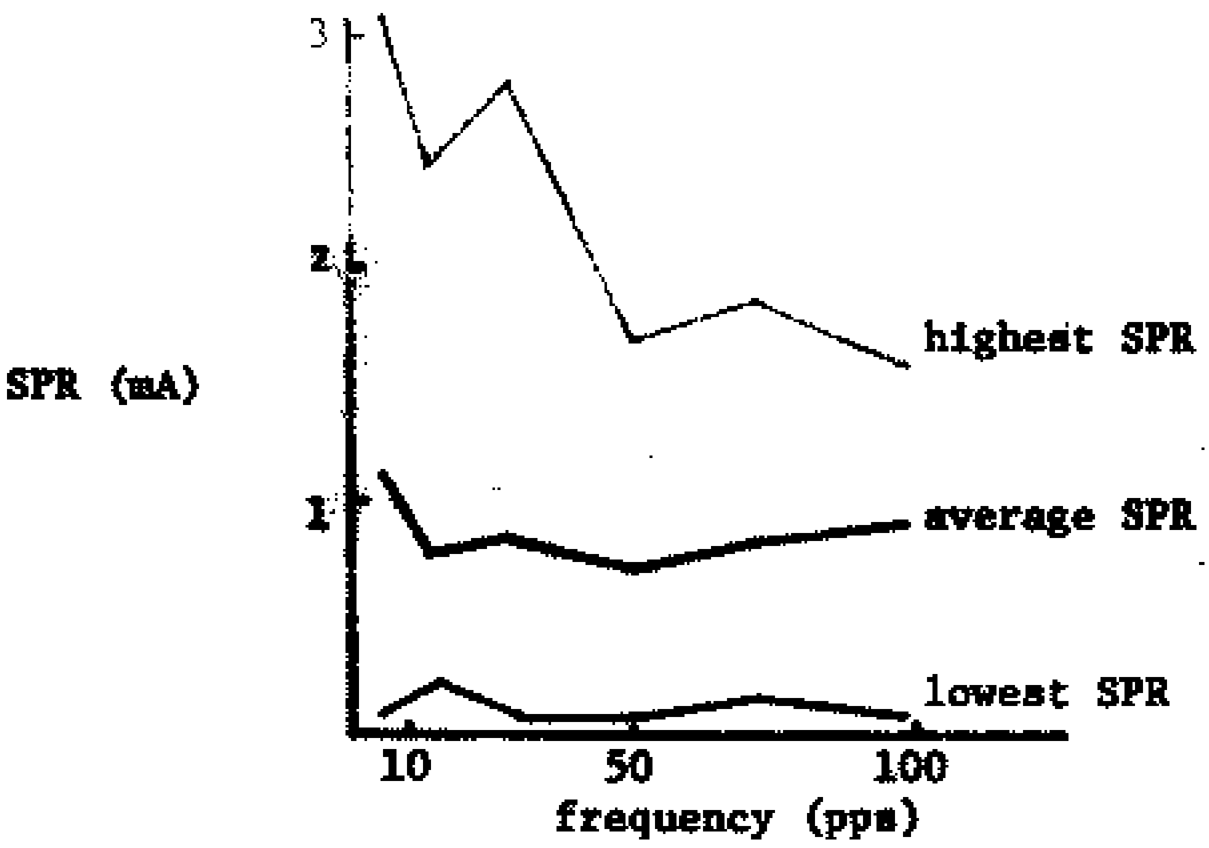

Figure 5. Sensation to Pain Range curves as a function of frequency, (average curve of all 14 subjects)

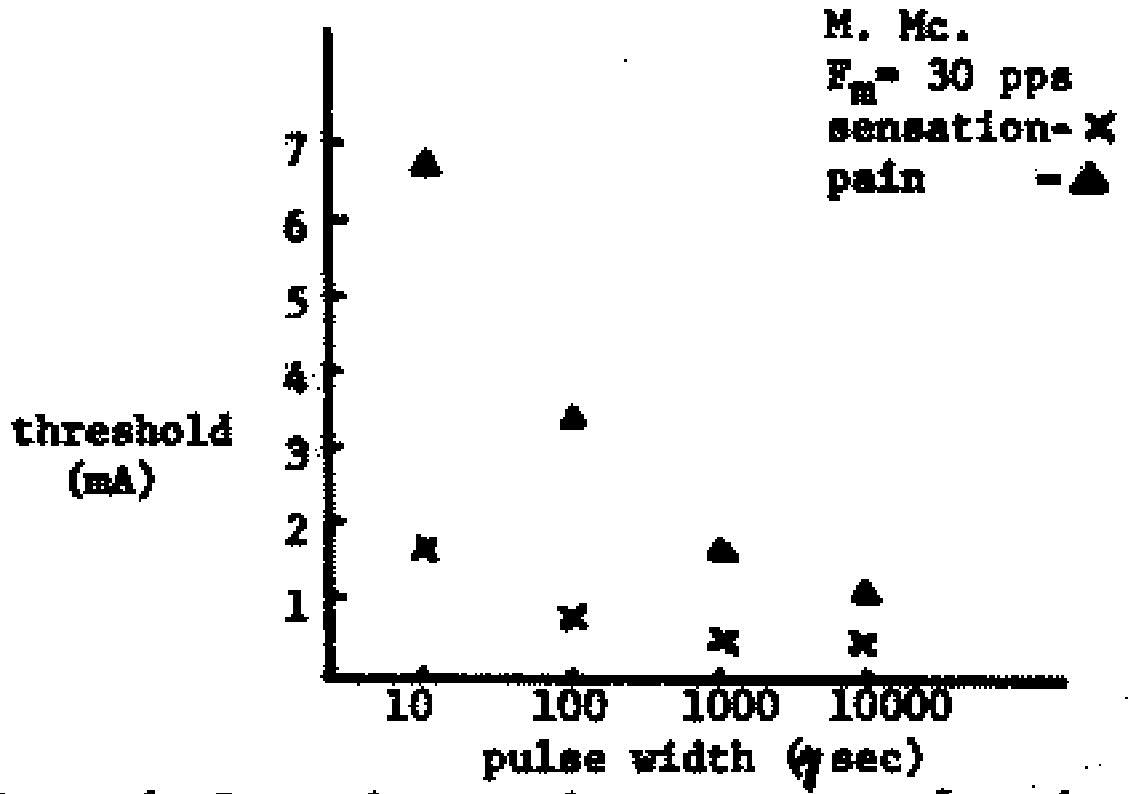

Figure 6. Sensation - pain curves as a function of pulse width for one subject.

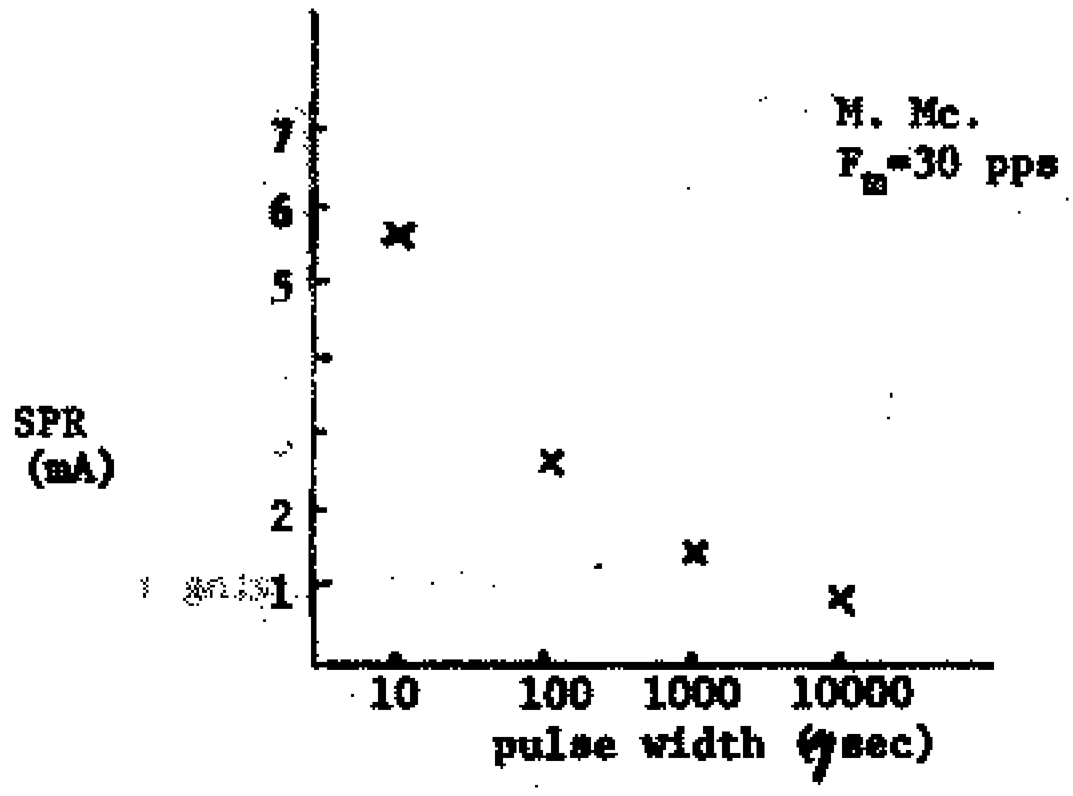

Figure 7. Sensation to pain range as a function of pulse width for fig. 6.

The FBW was measured for all subjects at 95 pps, with the exception of one subject whose FBW was 75 pps.

It is therefore apparent, that once the stimulus level is set just below the MPT, the complete frequency range of 0 - 100 pps is available for coding sensory information via the tactile sense.

Repeatability

In order to assess the repeatability and accuracy of the measurements, the average of three readings at MST was obtained, and the standard deviation (SD) of each reading was calculated. Table II below shows the average SD for all subjects as well as the largest and smallest SD.

TABLE II

$SD_{average}$	SD_{min}	SD_{max}
0.328 mA	0.023 mA	2.466 mA

Pulse Width

Typical plots of sensation and pain thresholds as a function of pulse width at the F_m of one subject are shown in Figure 6. Two major observations could be made regarding thresholds and range values.

The sensation and pain thresholds at 10 μs are approximately twice their value at 1 ms, which follows closely the well known strength-duration relationships. Furthermore, a three to four fold decrease in the SPR is apparent from pulse widths of 1 ms to 1 μs as shown in Figure 7. For practical purposes it may be advantageous to employ narrow pulse width so large SPR is available to compensate for variations in skin impedence in dryness and prespiration without exceeding the thresholds into pain or below sensation. Such implications of narrow pulse width use are in clarity of perception, reliability of the display interface, quantity of information transmission, as well as patient safety and comfort.

Conclusions

Based on our findings, it could be concluded as follows:

1. The electrotactile sensations and pain thresholds are functions of frequency.
2. Over the frequency range of 0 - 100 pps exists a minimum sensation and pain thresholds, MST and MPT respectively.
3. Both MST and MPT occur at the same frequency F_m.
4. The F_m is constant for the same subject but varies from subject to subject in the range of 0 - 50 pps.
5. The minimum sensation, pain and two point discrimination thresholds occur at the same F_m.
6. The FBW is 95 pps for nearly all subjects.
7. Stimulus of 10 μs widths results in the highest sensation and pain thresholds.
8. Pulse widths of 10 μs allow SPR of three to four folds larger than widths of 1 ms.

9. Sensation and pain thresholds are exponential functions of stimulus pulse width.

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